USGS

WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Investigation into the Effect of the Direction, Spatial Coverage and Temporal Distribution of Rainfall on Watershed Flooding

Focus Categories: Flooding (FL), Hydrology (HYDROL), and Surface Water (SW)

Keywords: Drainage, flooding, rainfall, rainfall-runoff models, watershed modeling, and urban hydrology

Duration: 12 months. Starting date: 3-1-2000, and ending date: 2-28-2001

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Statement of Critical Regional Water Problems

The Gulf Coast region (GCR) is perhaps one of the most flood prone areas in the United States. This is even more true in Louisiana where flooding is a regular annual occurrence in one part or the other. For example, the 1995 related floods of southeast Louisiana and Mississippi claimed seven lives and resulted in property damage estimated at over 3 billion dollars. Landfalling hurricanes occur frequently during the hurricane season and cause extensive flooding and property damage. In 1992 hurricane Andrew made a landfall in Florida and Louisiana resulting in 58 deaths and caused over 30 billion dollars of property damage. These damages were attributed in part to the heavy rainfall which caused extensive flooding.

The flooding patterns are greatly influenced by climatic factors. Climatic anomalies such as El Nino also affect the spatial distribution of the amount and intensity of rainfall and its intensity. Laboratory experiments conducted in Canada, Europe and the U. S.; and field observations indicate that the speed, duration, and areal coverage of storms moving across a drainage basin exert considerable influence on flood characteristics. This is especially true in the Gulf Coast region and in Louisiana. The storm movement is also subject to significant long and short term variability. However, the effect of the storm movement and its ensuing characteristics, such as direction, duration, and partial coverage of the watershed have not been incorporated in hydrologic modeling and design. The usual practice in hydrologic modeling and design has been to consider rainfall storms to be stationary and covering the whole watershed. This is true of the design of urban drainage facilities as well as other civil works. Therefore, it is reasoned that drainage works, flood control projects, and other civil works must be designed, taking into account the effect of storm movement, direction, duration and spatial coverage. This would require a re-examination of the way design storms and design floods are computed.

Results, Benefits and/or Information Expected

This project will lead to a methodology demonstrating the significance of the direction, duration and areal coverage of moving storms on watershed runoff on both small and large watersheds. Both urban and rural watersheds will be included in the project. The results so derived will be useful in design of drainage facilities, flood control works and other civil works. The methodology will also be useful in nonpoint source pollutant transport, where flow of water or surface runoff is the primary agent for transporting pollutants. The results will demonstrate that hydrologic modeling and design procedures need a re-examination and re-evaluation. A computer program for application of the methodology developed and for carrying our computations for storm movement will be developed and made available.

The results of the project will provide a basis for revising the procedures for rainfall-runoff analyses and consequent rationalization of hydrologic designs. This will have significant engineering and economic repercussions. The information so gained will be of significance in planning, designing, evaluating and managing flood control and evacuation works. In such projects, information on the lead time is of crucial importance and inclusion of storm movement is vital in accurately predicting this time.

Nature, Scope and Objectives of Research

Flood events in Louisiana are manifestations of processes which occur at multiple temporal and spatial scales on a watershed. These processes are affected by a multitude of factors, including physical watershed characteristics, antecedent soil moisture condition, and meteorology of climatic events which cause flooding. A particularly complex issue is the spatial and temporal distribution of the factors which contribute to flooding. An important factor affecting the spatial distribution of flooding in Louisiana is due to the rainfall produced by fronts. This is especially true of cold fronts which can produce significant amounts of rainfall causing extensive localized flooding. The intensity, speed and direction of these fronts are heavily influenced by weather conditions over the Gulf of Mexico. For example a moving cold front can become a stationary front if there is a high pressure system over the Gulf and when the high pressure system dissipates, the front starts to move again. These relatively abrupt changes in speed and direction of the front result in rainfall distribution patterns which are nonuniform in space and time. The associated flooding patterns due to such rainfall events tend to be intense and local in nature and do not lend themselves to simple characterizations based on stationary rainfall fields. Traditional hydrologic models which do not take into account the effects of storm movement would perform poorly in predicting the temporal and spatial distributions of flooding. This results in inaccuracies in the spatial flooding patterns and explicitly affects prediction of localized flooding.

A vast amount of research has been conducted on the effects of spatial distribution of topographic and soil characteristics, as well as the distribution and intensity of rainfall. However, most currently available flood hydrology models represent the weather system associated with a particular flood as a static event. Thus, a particular spatial and temporal distribution of rainfall is chosen to represent the event and the movement and the direction of the storm across the watershed is usually not considered. In fact, in most prevalent models employed by the National Weather Service for flood forecasting, even the spatial distribution of rainfall is smoothed by the use of the mean areal precipitation values.

A major drawback of most flood hydrology models currently employed is the assumption that rainstorms are stationary and they fully cover the watershed under study. This assumption is not valid for the GCR and Louisiana where the bulk of rainfall is produced by moving rainstorms. The importance of storm movement on generation of surface runoff was recognized as early as 1964 by Maksimov (1964). Singh (1997a) critiqued the studies dealing with the effects of storm movement on flood hydrograph. Storms may move in any direction depending on the local weather conditions prevailing at that time. The direction of storm may be downstream, upstream, across stream and angular to stream. Analytical studies conducted by Singh(1997b) show that a storm moving downstream produces a higher peak than a storm moving upstream. The time to peak is longer for downstream moving storms than for upstream moving storms. Likewise, of the storms moving downstream at different velocities, the storm moving at the velocity of flow produces the highest peak. Furthermore, the areal coverage-the extent and location of the watershed area covered by the storm plays a critical role in flood generation.

The effect of storm movement and spatial coverage is accentuated when infiltration is simultaneously incorporated in hydrologic analyses. Interestingly, this effect conforms to what is observed in partial-area hydrology. The importance of storm movement becomes even more critical in case of local flooding when the storm duration is short.

Acknowledging the significance of storm movement on flood hydrology , the objective of this research project is to develop a methodology for quantitatively determining the effect of spatial, temporal, and directional distribution of rainfall on watershed flooding. Specifically, the following specific objectives are defined:

1. To determine the effect of the direction of storm movement on watershed flooding

2. To determine the effect of partial coverage by the storm on watershed flooding

3. To simultaneously determine the effect of the direction and partial coverage on watershed flooding

4. To develop a computer program for accomplishing the objectives 1 through 3 above

5. To verify the results of objectives 1 through 3 above through simulation and experimental and filed data.

Methods, Procedure and Facilities:

Spatial and temporal distribution of rainfall is one of the main factors affecting watershed runoff, and this distribution is significantly affected by the direction and duration of storm movement. The direction of storm movement can be distinguished as upstream, downstream, across stream and angular to stream. Furthermore, the spatial distribution of rainfall can encompass a broad spectrum of scenarios: (1) The rainfall storm can cover only a portion of the watershed on the downstream side. (2) The rainfall storm can cover only a portion of the watershed on the upstream side. (3) The rainfall storm can cover different portions of the watershed. (4) The rainfall occurs nonuniformly over the watershed. For the same amount and temporal distribution of rainfall, the flooding patterns will be significantly different from one scenario to the other.

Furthermore, when the movement of rainfall is considered simultaneously with infiltration, the effect of storm movement is even more accentuated. How much impact there will be remains to be investigated. A methodology will be developed by using the kinematic wave theory which is an accepted tool for rainfall-runoff modeling these days. Thus, the problem of quantitatively determining the effect of storm movement will be formulated as follows:

Consider a plane of length L, width W, and slope S. A storm with a velocity of V travels on a plane. Let the storm be of duration T and intensity q in space and time:

$$q = 0,\ t \le 0;\ q \succ 0,\ \ 0 \le t \le T;\ q = 0,\ t \ge T \succ 0 \qquad (1)$$

The continuity equation for planar flow can be written on a unit width basis as:

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q\,(x, \xi) \qquad (2)$$

where h is the depth of flow, Q is the flow discharge per unit width, x is distance along the direction of flow, t is time, and > is the time for which the storm covers the plane defined as

$$\xi = t - \frac{x}{V} \tag{3}$$

in which V is the velocity of rainstorm. The kinematic depth-discharge relation is expressed as

$$Q = \alpha h^{n} \tag{4}$$

where " is the kinematic wave roughness parameter, and n is the kinematic wave exponent. Equation (4) is a rating curve equation specializing in standard flow equations, such as Chezy's, Manning's, Darcy-Weisbach' Hazen-Williams', etc.

Equations (1)-(4) will be utilized to develop a methodology for determining the influence on watershed flooding of the following: (1) Storm direction-in which storms may move upstream, downstream, across stream or angular to stream on a watershed but fully cover it. (2) Storm coverage-in which storms cover only a portion of the watershed in a variety of ways: a portion downstream, a portion upstream, different portions on the watershed, etc. (3) Storm direction and areal coverage- in which storm direction and partial coverage are simultaneously considered. (4) The above three cases are combined with the case when infiltration is simultaneously considered.

The methodology will include three parts: First, an analytical treatment of the effect of storm movement and direction considering the above cases will be derived. This issue does not appear to have been reported in the literature. Most of the studies reported in the literature have either been numerical or empirical. Analytical solutions provide considerable insight into the relation between storm dynamics and flow dynamics. By comparing the flow due to a moving storm with that due to a stationary storm of the same duration the influence of storm direction and duration on flow hydrograph will be investigated. This will be done for partial coverage of the watershed by the storm.

Second, numerical solutions will be developed for the cases where the rainfall storm has temporal variability. These solutions will be developed using the Lax-Wendroff scheme (Singh, 1976). Third, the analytical and numerical solutions will be verified using simulation as well as the data reported in the literature. An attempt will also be made using data from small watersheds in Louisiana. Fourth, a computer program will be developed to execute the methodology developed and made available for use.

The proposed model can be easily adapted to model the spatial and temporal distribution of rainfall due to fronts by incorporating such frontal characteristics as speed, direction and weather conditions over the Gulf of Mexico. This model can then be coupled to a two dimensional rainfall-runoff model to accurately describe the flooding patterns. The coupling of d models would constitute the subject matter for future research.

Related Research:

Maksimov (1964) recognized the importance of storm movement on surface runoff and showed that the rainstorm movement altered peak discharge. In a laboratory study Marcus (1968) showed the importance of the rainstorm movement to the time distribution of surface runoff. There have since been a number of investigations dealing with the influence of storm movement on watershed runoff. Singh (1997a) has given a survey of such investigations. Roberts and Klingman (1970) found that the direction of storm movement might augment or reduce flood peaks and modify the hydrograph recession. Surkan (1974) observed that peak flow rates and average flow rates were most sensitive to changes in the direction and speed of the rainstorms. Niemczynowicz (1984a,b) determined the influence of storm direction, intensity, velocity, and duration on the runoff hydrograph and peak discharge on a conceptual watershed and a real watershed in the City of Lund in Sweden

Yen and Chow (1968) undertook a laboratory investigation of surface runoff due to moving rainstorms. Sargent (1981, 1982) determined the effects of storm direction and speed on peak runoff, flood volume, and hydrograph shape. Stephenson (1984) simulated runoff hydrographs from a storm travelling down a watershed. Jenson (1984) determined the influence of storm movement and its direction on the shape, peak, time to peak and other characteristics of the runoff hydrograph. Foroud et al. (1984) employed a 50-year hypothetical moving rainstorm to quantify the effect of its speed and direction on the runoff hydrograph. Ngirane-Katashaya and Wheater (1985) analyzed the effect of storm velocity on runoff hydrograph. Ogden et al. (1995) investigated the influence of storm movement on runoff. Singh (1997b) examined the effect of the direction of storm movement on planar flow. In all of these studies a systematic treatment of the storm movement and the various issues connected with it in surface runoff modeling has not been developed and this project will attempt to do that.

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